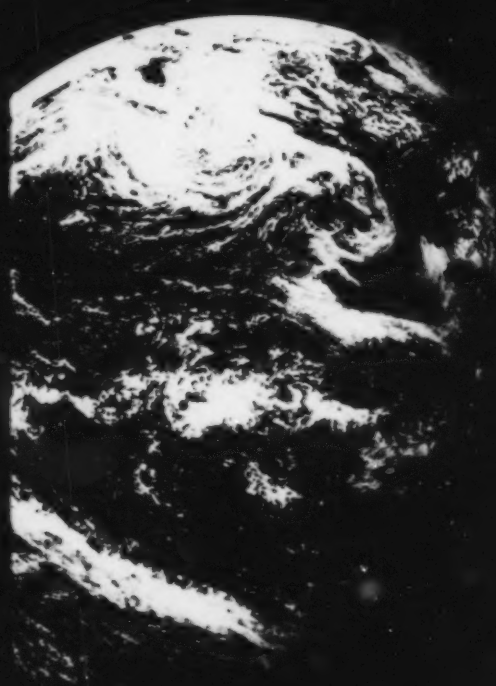
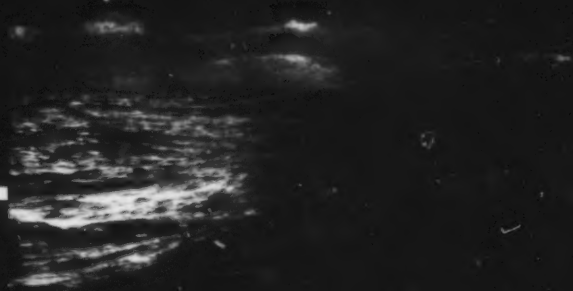


Canada's Contribution to:

WOCE



The
World
Ocean
Circulation
Experiment



WOCE

Introduction

The further we try to predict into the future, the less accurate the results. This is because the weather that arrives tomorrow is influenced mostly by local conditions while the weather due in five days can be affected by things happening a continent away. Obviously, trying to discover general weather changes over months and years (climate change) requires an understanding of global proportions. It is in this context that the true significance of the oceans in long-range weather prediction and climate change is demonstrated.

The oceans are as important to the formation of weather and climate as is the atmosphere itself. Unfortunately, our understanding of them is limited. To be able to include the oceans factor in computer equations to improve long-range weather and climate predictions, we must first study and understand ocean/atmosphere interactions — an enormous task given the vast, sometimes hostile ocean surface to be covered (three-quarters of the planet) and the fact that measurements must be taken several miles down to the ocean floor.

To help answer some of the questions, Canada has joined approximately 40 other countries in a global program called the World Ocean Circulation Experiment (WOCE). Its purpose is to develop an understanding of how the oceans influence climate, and to determine how best to measure the oceans to improve future climate forecasts.

This brochure provides some background for understanding WOCE and describes the research carried out by Canadian scientists within the international program.

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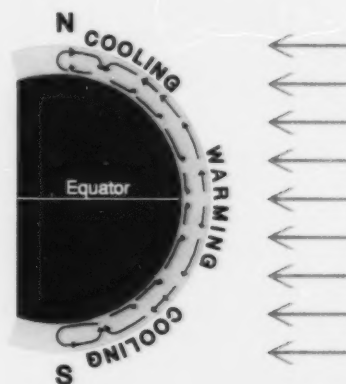
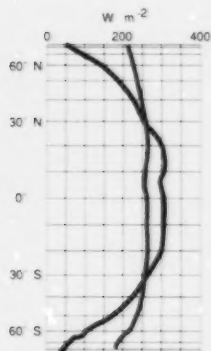
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Oceans and Climate

The Sun warms the Earth; it does so most effectively in the tropics. The ocean shares with the atmosphere the task of redistributing heat poleward. On a long-term average, an equilibrium is reached: the Earth's surface temperature adjusts itself to send back out to space as much heat as it receives from the Sun.

Meteorologists have by now documented the wind systems which carry heat towards the poles. Computer models of the general atmospheric circulation are in daily use for weather forecasting; predictions are stretched over decades to arrive at climate forecasts.

Fig. 1: Radiation balance for the Earth. The blue curve shows the amount of solar radiation absorbed at the earth's surface. Near the poles the amount of outgoing long-wave radiation (the red curve) exceeds the amount of solar energy absorbed, and the opposite is true in the tropics. The atmosphere and oceans carry heat poleward, thereby affecting the energy balance.



The oceans, however, are still poorly explored. Their role in moderating coastal climate has of course long been recognized. More recently however, oceanographers have discovered that ocean currents recirculate about as much heat as the atmosphere does, but in a more complicated way. Furthermore, because of their great heat capacity and of the nature of their deep circulation, oceans can take centuries to adapt to climate change!

Climate modellers have identified their lack of ability to model ocean circulation and processes as one of the greatest barriers to improving their ability to predict climate change and variability. Canadian scientists and others around the world have joined together to plan and carry out the World Ocean Circulation Experiment (WOCE): the first global ocean program focused on the development and the validation of ocean models useful for climate prediction.

WOCE is an international program, 10 years in preparation and involving more than 40 nations. It will observe, analyse and model the global ocean to obtain a working, quantitative understanding of its role in the Earth's climate system. Scheduled to run 10 years (1990–2000), the first half of its life span will concentrate on an intensive observational program.

WOCE is sponsored by UNESCO's Intergovernmental Oceanographic Commission, the World Meteorological Organization's World Climate Research Program, the International Council of Scientific Unions and its Scientific Committee on Oceanic Research.

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Upper Ocean

The upper ocean is affected by the wind as well as by fluxes of heat and water vapour. The wind creates waves, pushes the ocean along in a system of currents, and helps mix waters vertically.

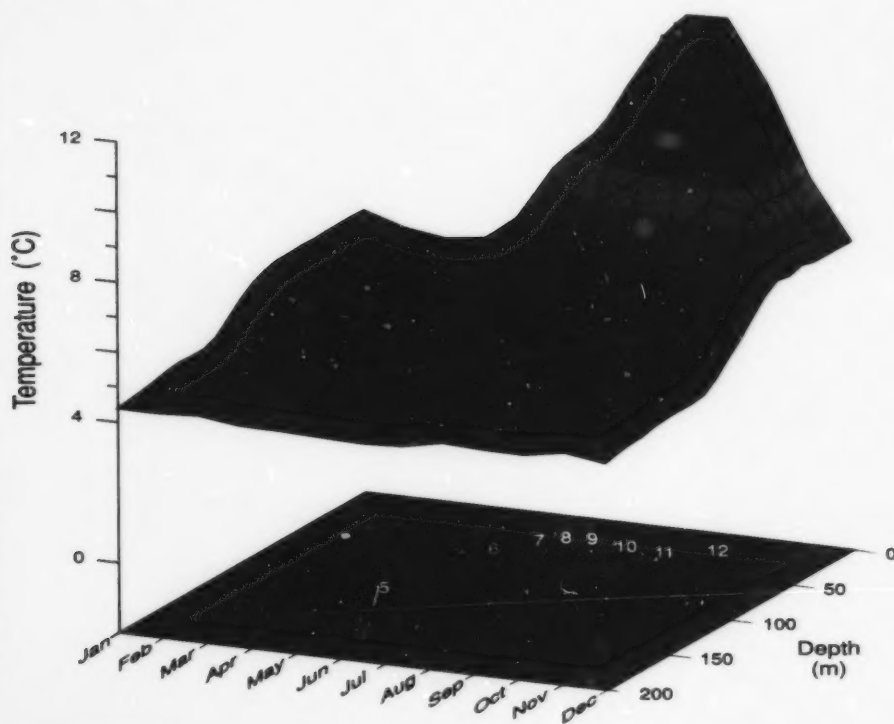


Fig. 2: Two views of the distribution of water temperature over a year in the upper 200 m in the central Pacific at Ocean Weather Station "PAPA". Above is a perspective three-dimensional graph of the water temperature. Below is a contour plot of the same data. A thermocline develops between July 15 and October 15 in depth.

Surface waters are cooled by contact with cold air masses, by radiating their heat into space and by evaporation. They are warmed by sunlight and by contact with warm air masses. Warm water floats above cooler water of the same salinity. Sharp temperature gradients called "thermoclines" are formed near the ocean surface. They change their strength and depth with the seasons.

As water is cooled, it sinks to depths where it will be in equilibrium with waters of the same density. The sinking process, called convection, destroys the thermocline, or at least takes it down to greater depths.

In very cold areas, such as Antarctica or the North Atlantic, convection is so intense that it reaches to the bottom of the ocean. This deep convection process is thought to be intermittent and localized to "chimneys" a few kilometres across. The process of deep-water formation by convection is extremely important in considering the role of the ocean in climate. Because deep ocean waters (below 2,000 m or so) are isolated from contact with the atmosphere after the convection process, they respond only very slowly to climate change.

WOCE

Ocean Currents

There are two kinds of ocean currents. Wind-driven currents on an ocean-size scale are arranged in large "gyres". In the North Atlantic, for example, one recognizes a sub-tropical and a sub-polar gyre. Strong currents (the Gulf Stream, the Labrador Current) are concentrated on the western side of the ocean and contribute significantly to poleward heat transport. Similar gyre systems are formed in other oceans as well: for example, in the northwest Pacific, the Kuroshio and Oyashio are the analogues of the Gulf Stream and Labrador Current respectively.

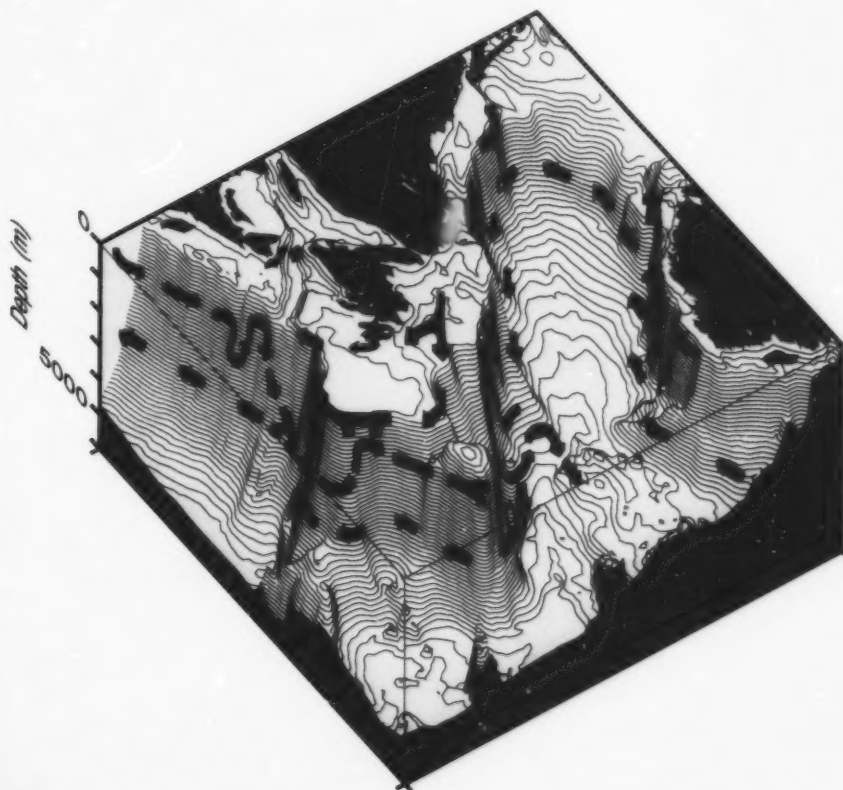


Fig. 2. A perspective view of the three-dimensional map of the bathymetry and isopycnal surfaces in the North Atlantic Ocean. The white, wavy lines represent isopycnal surfaces and the black lines represent bathymetry.

The other kind of current system is driven by the sinking of cold, salty waters. This "thermohaline" circulation occurs at great depths and transports these waters throughout the world ocean. Its currents are slow compared with the wind-driven currents and remain poorly documented.

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WOCE Objectives

The ocean has many processes, many scales of variability and motion that are neither well described observationally nor well understood. As a first step in the planning process, the WOCE Scientific Steering Group established a formal set of goals and objectives for the experiment as a whole. These guide WOCE planners when they are deciding what type of work must be included and what can be excluded. These goals and objectives are:

Goal 1: To develop models useful for predicting climate change and to collect the data necessary to test them.

Within Goal 1, the specific objectives are: To determine and understand on a global basis the following aspects of the World Ocean Circulation and their relation to climate:

- (1) The large-scale fluxes of heat and fresh water, their divergences over five years and their annual and interannual variability.
- (2) The dynamic balance of the World Ocean Circulation and its response to changing surface fluxes.
- (3) Components of ocean variability from months to years, megametres to global scales, and the statistics of smaller scales.
- (4) The rate and nature of formation, ventilation and circulation of water masses that influence the climate system on time scales of 10 to 100 years.

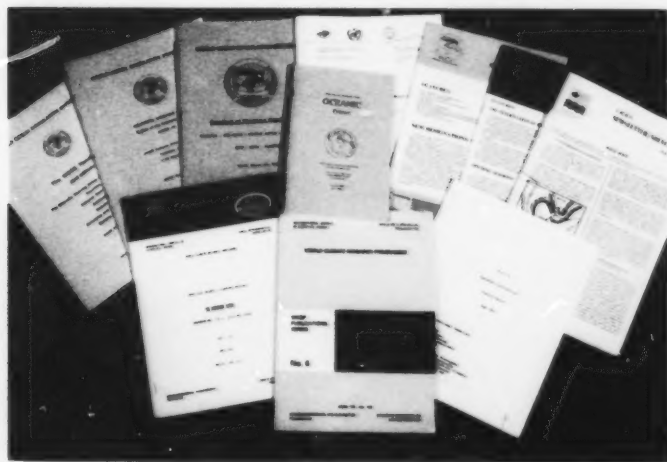


Fig. 4: Collage of covers of WOCE reports, Science Plan, Implementation Plan, WOCE Conference Report, WOCE News, etc.

Goal 2: To determine the representativeness of the specific WOCE data sets for the long-term behaviour of the ocean and to find methods for determining long-term changes in the ocean circulation.

Within Goal 2, the specific objectives are:

- (1) To determine the representativeness of the specific WOCE data sets.
- (2) To identify those oceanographic parameters, indices and fields that are essential for continuing measurement in a climate-observing system on decadal time scales.
- (3) To develop cost-effective techniques suitable for deployment in an on-going climate observing system.

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WOCE's Core Projects

The WOCE field program is coordinated scientifically within three core projects.

Project 1, The Global Description will measure the momentum, heat and water flux between atmosphere and ocean; the seasonal response of the upper ocean to that forcing; the three-dimensional mean circulation; and the distribution of eddy energy. The project relies heavily on satellite measurements of wind, temperature and sea level, coupled through computer models with scattered, high-quality measurements at sea to produce global estimates. It encompasses the Atlantic Ocean from Labrador, Greenland, Scotland to the tip of South America and the entire Pacific and Indian oceans.

Project 2, The Southern Ocean, will measure similar quantities as in Project 1 but in the Southern Ocean, concentrating on the exchange of waters among the Atlantic, Indian and Pacific oceans and the formation and spreading of its dense intermediate and deep waters.

Project 3, The Gyre Dynamics Experiment, will focus on specific processes which must be better understood and modelled to improve our climate prediction capabilities. These process experiments are located primarily in the Atlantic Ocean (between 30°S and 60°N) and when combined with an enhanced set of Project 1 measurements will provide a North Atlantic data set more suitable for gyre-scale ocean model development and testing.

Canada's contribution to the WOCE field program will be in projects 1 and 3, in both the Atlantic and Pacific oceans.



WOCE

WOCE's Hydrographic Program

Hydrography — the measurement and study of the distribution of temperature, salinity and chemical tracers in the ocean — is the traditional tool for studying ocean circulation. The WOCE Hydrographic Program consists of a series of continent-to-continent sections of full-depth hydrographic stations across every deep ocean basin and every known ocean gyre, running both east-west and north-south. It will provide the most accurate and detailed information on the global hydrography ever collected. Some sections will be repeated to determine seasonal and year-to-year variability. Canada will occupy both one-time and repeat sections in the North Atlantic and North Pacific oceans. Canada will contribute a total of 550 days of ship time to this programme during its seven-year lifetime, about 3% of the total ship resources required.

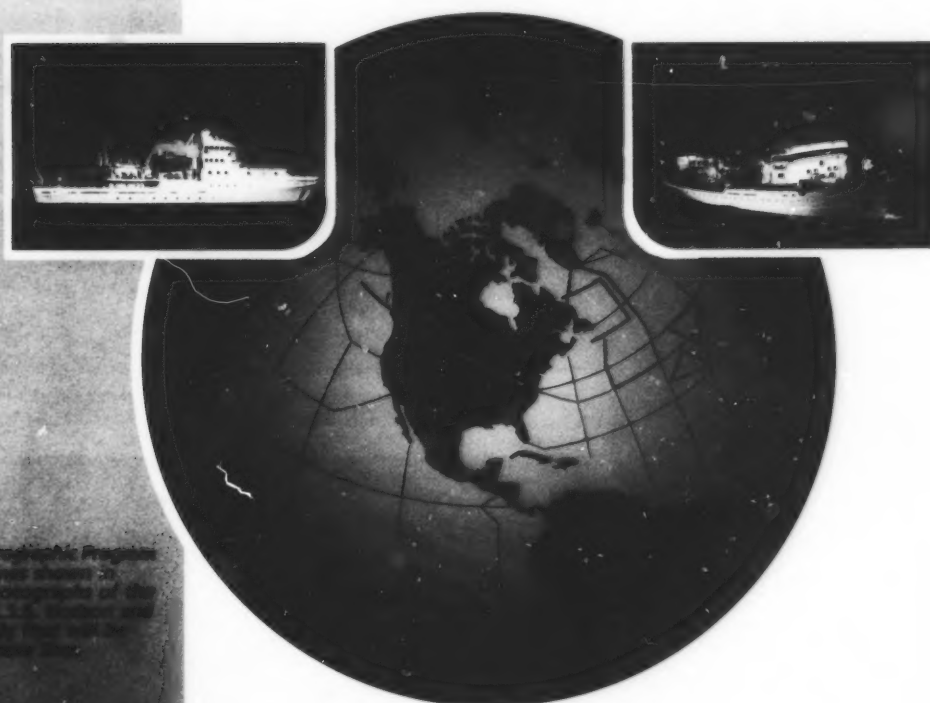


Fig. 6: WOCE Hydrographic Program lines. Canadian lines shown in red. Insets are photographs of the research ships C.S.S. Hudson and C.S.S. John P. Tully that will be used to survey these lines.

The global hydrographic data set, when combined with satellite observations and direct measurement of water movements by surface drifting buoys and deep floats, will detail the three-dimensional ocean circulation and its variability. In some key locations the deployment of moored arrays — anchored strings of current meters — will provide estimates of the volume transport of important currents, and of flow through several strategic deep passages. In other locations, current meters will provide information on the vertical structure of eddies, the oceanic equivalent of storms in the atmosphere and a key property that ocean models must be able to reproduce. Canada will deploy mooring arrays in both the Atlantic and Pacific oceans.

WOCE

Numerical Modelling and Experimentation

The information collected during WOCE's field program will form the foundation of the ocean climate-prediction models. Development of coupled ocean-atmosphere models will be pursued actively by WOCE researchers in many countries. High-resolution models, capable of following oceanic eddies, will be used jointly with observations to refine the understanding of intensively sampled areas such as the North Atlantic.

Canadian oceanographers will be working towards developing global ocean general circulation models. They will also be refining regional models developed over the past few years to study currents over Canada's extensive continental shelves, hoping to extend these models to explore the coupling between the deep ocean and the shallower shelf areas.

In the North Atlantic, simple numerical models will be utilized to test if coastal sea level, measured routinely by tide gauges and bottom pressure sensors, can be used to monitor the strength of wind-generated circulation. Regional models will be coupled with satellite-derived information in a technique called "data assimilation" to improve descriptions of ocean currents and of the heat and water vapour fluxes between ocean and atmosphere. The results of the models will be compared with observations of these properties in the same region.

The important process of deep-water formation, whereby cold and dense surface water sinks to great depths, is thought to take place in the Labrador Sea. A very high-resolution model of that area will be used to examine the conditions under which deep-water formation takes place.

Fig. 7: Numerical model of volume fluxes off Newfoundland.

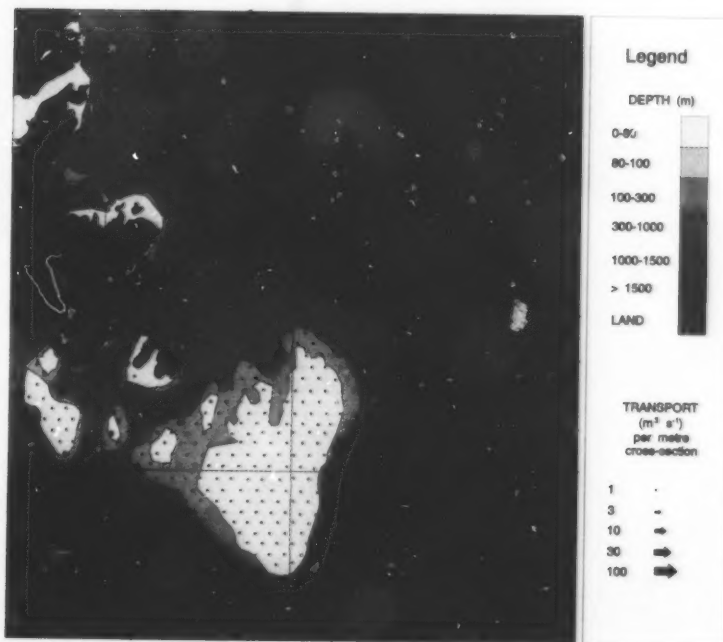
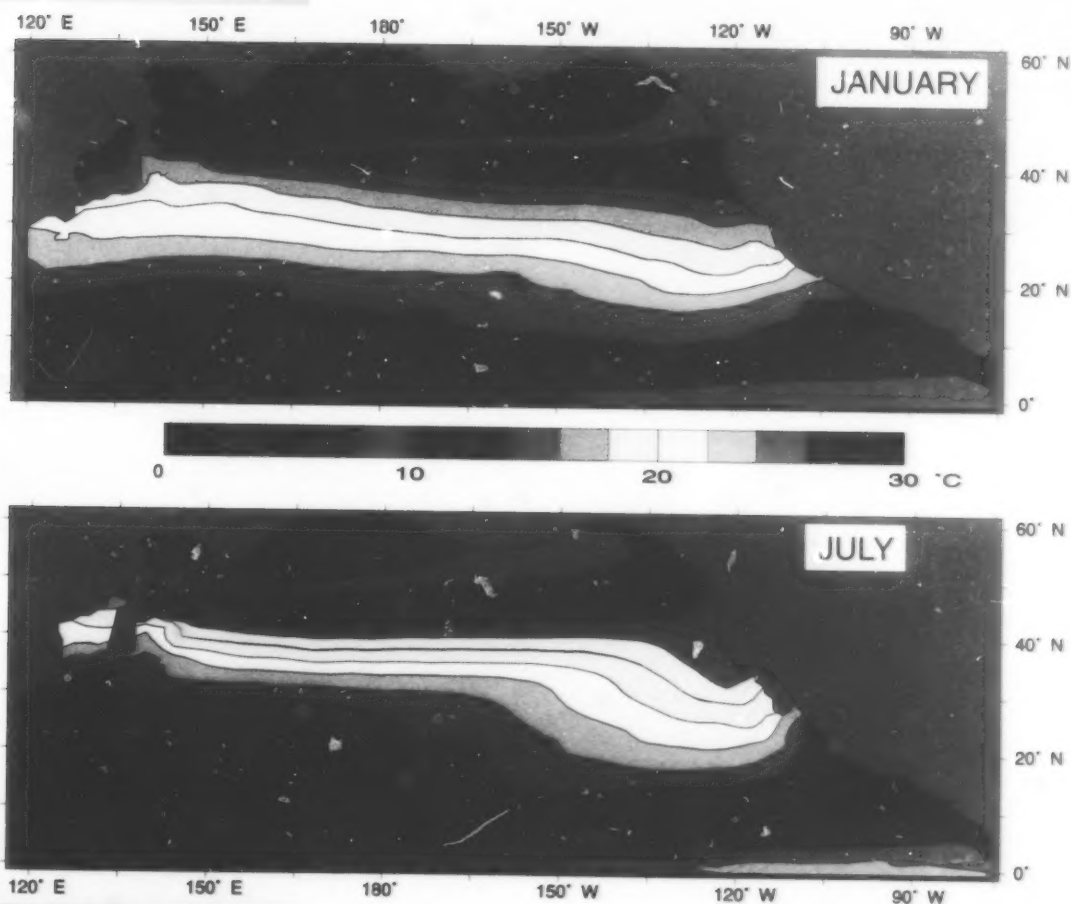


Fig. 8: Mixed layer temperature in January and July as simulated by the North Pacific Active Layer upper-ocean model, forced with seasonal climatological surface heat, freshwater and momentum fluxes.

In the North Pacific, numerical studies will take place with particular emphasis on how to use observations to correct a model. The North Pacific modelling effort will be supported by observation programs to improve regional estimates of air-sea fluxes and surface currents. (Resulting improvements in the understanding of large-scale, air-sea interactions in the North Pacific may in turn lead to improved reliability of long-term weather prediction.) A global ocean model will be set up to be coupled to the atmospheric model run by the Canadian Climate Centre. This type of coupled atmosphere-ocean model is needed to study global climate change.



WOCE

Eyes in the Sky

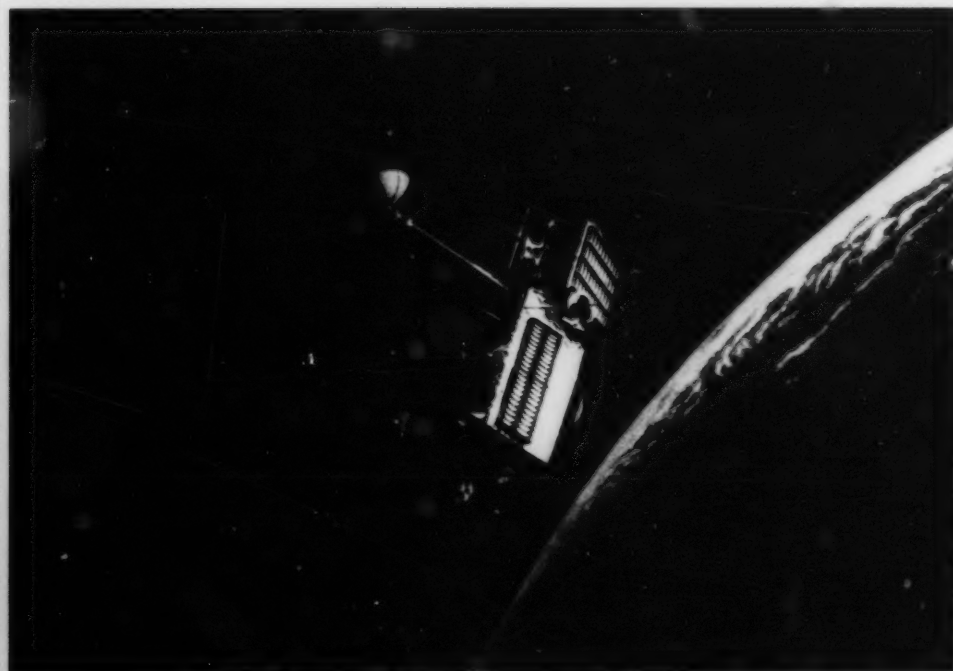
The availability of the new satellite-borne, remote-sensing devices since the 1980s has revolutionized oceanography and made possible WOCE's ambitious effort to accomplish a comprehensive survey of the global ocean. Satellite missions during WOCE, conducted on a repeat-orbit basis, will provide the most complete global measurements ever made of ocean-surface topography, winds and temperatures.

Canadian oceanographers will continue to use visual, infra-red and microwave imagery from satellite-mounted instruments to study the evolution of sea-surface temperature and sea-ice distributions in Canada's offshore waters. Actual temperature measurements from the sea surface and ice-mounted sensors will be distributed to global data centres to validate and control the world-wide information collected by satellite for WOCE.

For the first time since the short-lived SEASAT mission of the 1970's, scatterometer instruments will provide all-weather estimates of the surface winds over the global ocean. Canada will conduct offshore wind/wave experiments to collect *in situ* validation and calibration data for the scatterometers aboard the ERS-1 satellite and the later NSCAT/ADEOS satellite mission.

SEASAT and another satellite, GEOSAT, used radar altimeters to measure small deviations in sea level; the TOPEX/POSEIDON satellite will be launched during WOCE to collect accurate sea level measurements.

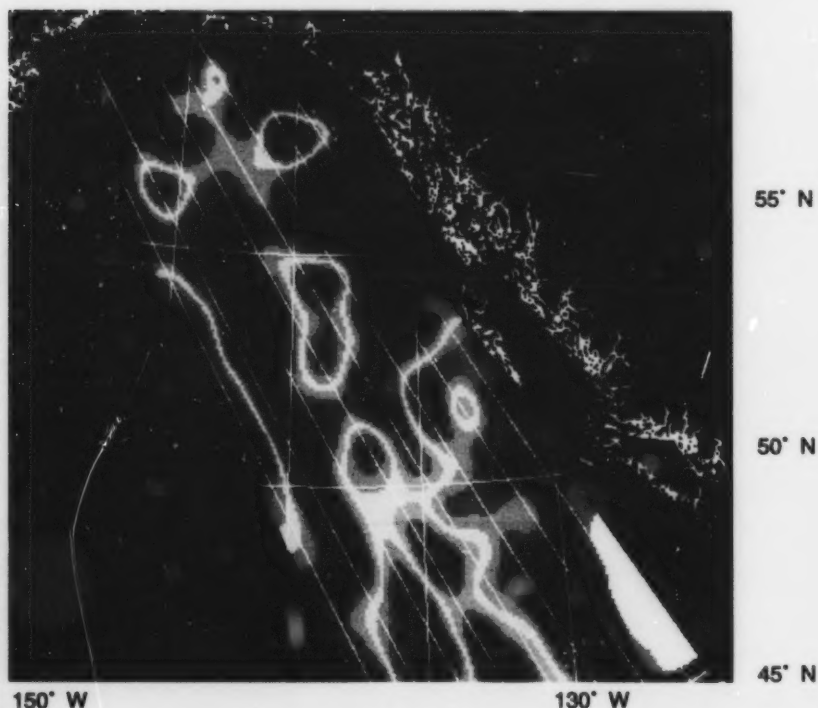
Fig. 9: TOPEX/POSEIDON satellite that will be used in WOCE.



WOCE

Surface Altimetry

To a casual observer, the sea surface on a calm day looks perfectly flat. Nevertheless, small sea surface slopes, associated with changes in level of only a few centimetres, are important in driving ocean currents.



The time-dependent topography of the sea surface gives oceanographers the equivalent of the meteorologist's surface pressure maps. The ocean's surface currents are related to the slope of the sea surface in the same way that winds are related to atmospheric pressure fields. For example, across strong currents such as the Gulf Stream, which sweeps up the United States coast and veers east across the Atlantic, the sea level rises about 1 m in 100 km.

Oceanographers will use satellite-mounted radar altimeters to measure the elevation of the sea surface and detect changes in sea level to an accuracy of a few centimetres. Canadian researchers on both the Atlantic and Pacific coasts will combine this information with actual ocean data and models to estimate circulation changes in Canada's offshore waters.

WOCE

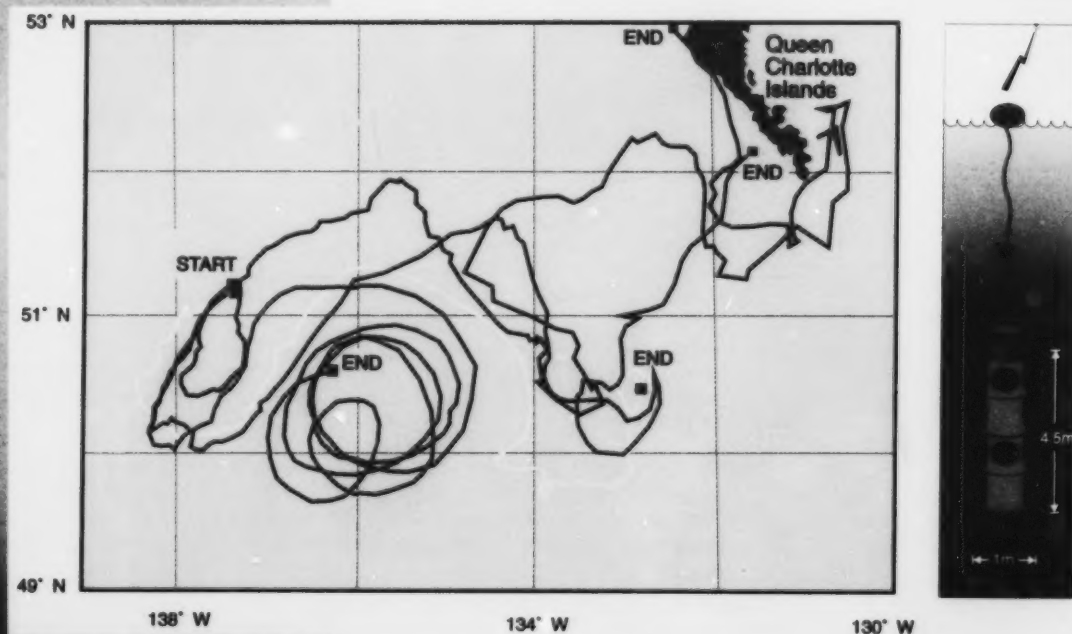
Surface Velocity Program

Another way of measuring ocean currents is to follow the path of drifting buoys. WOCE has developed an improved surface drifter which will provide precise estimates of the current at a depth of 15 m. Such drifters will measure water temperature along their paths; some will also measure atmospheric pressure and assist in weather prediction. Drifter positions are obtained by radio communication with Earth-orbiting satellites.

Canada's job is to set 20 drifters a year into the Alaska gyre as part of the global set. Maps of the surface circulation of the northeast Pacific will be compiled and combined with the upper-ocean temperature and salinity data collected by Canadian and other agencies in order to relate circulation changes to variability in the region's atmospheric fluxes.

As part of their contribution to WOCE, a number of countries are establishing archival centres for particular data sets. Canada will provide the archival centre for the data collected by various nations under the Surface Velocity Program. It will be located at the Marine Environment Data Service of the Department of Fisheries and Oceans in Ottawa.

Fig. 11: Drifter tracks off the B.C. coast. Daily positions during the first 150 days for the 4-buoy point-source deployment on 10 October, 1987. Inset is a sketch of a drifter used to collect these data.



WOCE

Deep Convection and Oceanic Variability



Fig. 12: "Great Oceanic Conveyor Belt" from "What Drives Global Cycles" by W.S. Broecker and G.H. Denton. Copyright © 1989 by Scientific American, Inc. All rights reserved.

The oceans' deep and intermediate waters are formed by the sinking of dense waters in regions of intense cooling or active evaporation. The North Atlantic Ocean and its marginal seas — the Mediterranean, Labrador and Greenland seas — are some of the most important regions of the ocean for this process. It is through these convective processes that the deep ocean communicates with the atmosphere and gradually changes its thermal, saline and other properties. Convection serves as a principal route for the entry of carbon dioxide and atmospheric contaminants into the deep ocean.

During WOCE, Canada will occupy a hydrographic section across the Labrador Sea at the end of each winter, measuring year-to-year changes produced by convection in both the Labrador and Greenland seas. Other Canadian researchers will work to improve the estimates of precipitation, evaporation and heat flux over the northwest Atlantic, which will then be related through regional modelling with the observed variability. Similar processes taking place in the North Pacific may also be studied under an expanded WOCE program.

WOCE

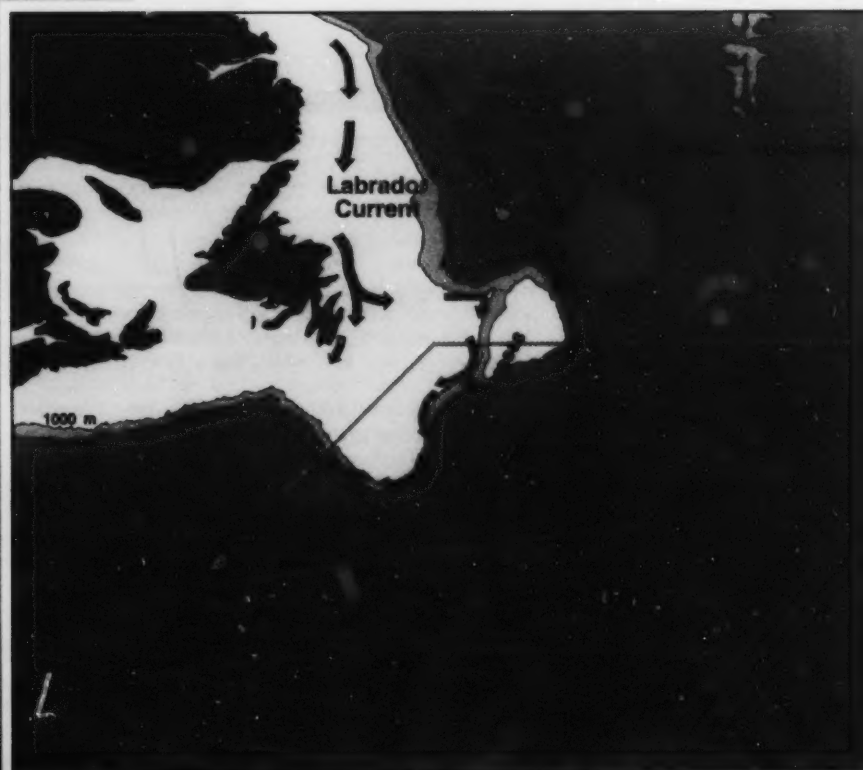
Control Volume Experiment

As part of Core Project 3 to study gyre dynamics, oceanographers will conduct a series of control volume experiments at several key locations of the North Atlantic circulation to study its variability. Canada will work with the U.S.S.R. to cover the area east of the Newfoundland Grand Banks during the period 1993-95.

From a gyre dynamics perspective, this region contains a number of important processes. It is here that the northward flowing waters of the Gulf Stream/North Atlantic current system divide into those that return southward within the sub-tropical gyre and those that continue northward in the sub-polar gyre. It is also in this area, and for reasons yet unknown, that a significant portion of the Labrador Current, carrying icy water down from Hudson Bay and Greenland, veers eastward off the edge of the continental shelf while the remainder continues down the coast. This is also a region of intense air-sea heat flux.

Canada will contribute considerable upper-ocean and full-depth hydrography and tracers, moorings, air-sea flux estimates and modelling in this complex region.

Fig. 13: Confluence of Labrador Current and Gulf Stream; also shown is the Control Volume Area.



WOCE

Ocean Mixing

Heat, salt and dissolved chemicals are carried through the oceans by horizontal currents (the large-scale circulation) and vertical currents (deep convection), as well as by the gentler, more disorganized effects of mixing. This mixing occurs at a variety of scales, making it difficult for researchers to reconcile results obtained in small-scale laboratory simulations with what is actually happening in the natural environment.

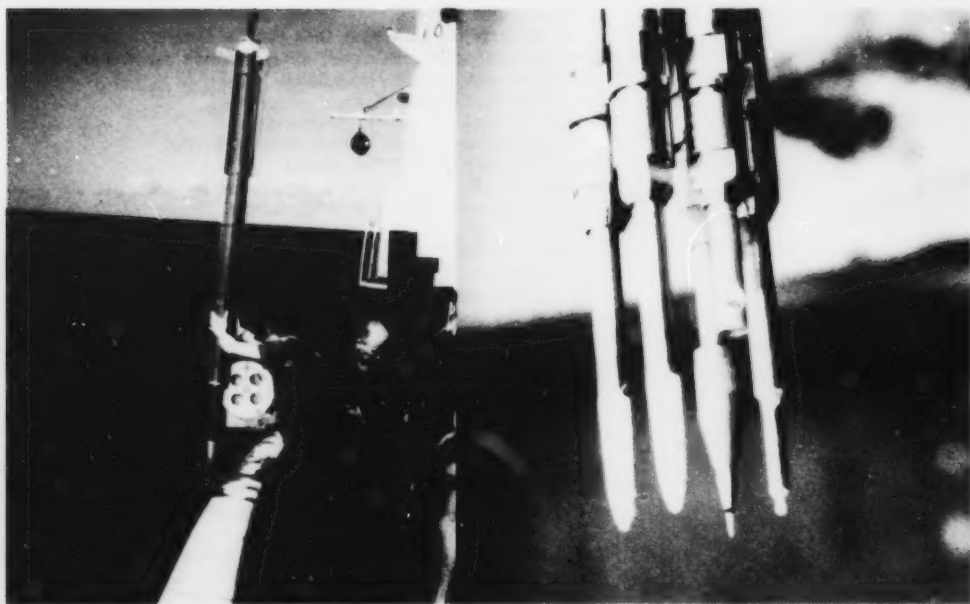


Fig. 14: EPPIC, an instrument developed at the Bedford Institute of Oceanography by N. Daley, measures turbulence levels in the context of WOCE being deployed at sea. At right: Integrated view of science team.

Canadian groups are at the forefront of the development and use of instruments to measure oceanic turbulence, and in the interpretation and analysis of these measurements in terms of physical processes and vertical mixing rates. Because these processes are intermittent in time and space, it is difficult to obtain averages that can be used in ocean models.

Within the WOCE Tracer Release Experiment, scientists will "paint" an area on a constant density surface about 30 km across with an easily detectable chemical tracer. They will visit the site at six-month intervals over a one-year period to determine how the tracer has mixed vertically. Canada will provide the deep-ocean turbulence measurements so that for the first time the small-scale estimates can be related to the larger picture.

Canadian scientists will also use a North Atlantic numerical model to study the interplay between mixing and circulation.

WOCE

Canadian participation in the World Ocean Circulation Experiment is funded by the Department of Fisheries and Oceans, by the Green Plan and by research grants from the Natural Sciences and Engineering Research Council of Canada.

Credits

The Canadian institutions participating in WOCE are:

Bedford Institute of Oceanography, DFO, Dartmouth, Nova Scotia
Institute of Ocean Sciences, DFO, Sidney, British Columbia
Marine Environment Data Service, DFO, Ottawa, Ontario
North West Atlantic Fisheries Centre, DFO, St. John's, Newfoundland
Dalhousie University, Halifax, Nova Scotia
McGill University, Montreal, Quebec
Memorial University, St. John's, Newfoundland
Royal Roads Military College, Victoria, British Columbia
University of Alberta, Edmonton, Alberta
University of British Columbia, Vancouver, British Columbia
University of Victoria, Victoria, British Columbia

Illustration Credits

Cover: NASA photo from Apollo 11 of the Pacific Ocean. It is late afternoon in western North America (upper right), and near midday the following day in Australia (lower left). At the top, the north polar cap gleams white.

Fig. 1: Diagram adapted from *Atmosphere-Ocean Dynamics* by A.E. Gill, Academic Press, 1982.

Fig. 2: Data for diagram provided by S. Tabata, Institute of Ocean Sciences.

Fig. 7: Adapted from "The Mean Barotropic Circulation on the Newfoundland Shelf and Slope" by D. A. Greenburg and B. D. Petrie, in *Journal of Geophysical Research*, Vol. 93, No. C12, 1988. Copyright by the American Geophysical Union.

Fig. 8: Adapted from a diagram provided by J. Cherniawsky, Institute of Ocean Sciences.

Fig. 9: Photograph provided by NASA.

Fig. 10: Image provided by J. Gower, Institute of Ocean Sciences.

Fig. 11: Adapted from "Analysis of Deep-drogued Satellite-tracked Drifter Measurements in the Northeast Pacific" by R.E. Thomson, P.H. LeBlond and W.J. Emery, in *Atmosphere-Ocean* 28(4), 1990.

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2. To determine the representativeness of the specific WOCE data sets for the long-term behaviour of the oceans and to find methods for determining long-term changes in the ocean circulation.

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